

Revival of the Thermal Sneutrino Dark Matter

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The left-handed sneutrino in the Minimal Supersymmetric Standard Model (MSSM) has been ruled out as a viable thermal dark matter candidate, due to conflicting constraints from direct detection experiments and from the measurement of the dark matter relic density. The intrinsic fine-tuning problem of the MSSM, however, motivates an extension with a new $U(1)'$ gauge symmetry. We show that in the $U(1)'$ -extended MSSM the *right-handed* sneutrino $\tilde{\nu}_R$ becomes a good thermal dark matter candidate. We identify two generic parameter space regions where the combined constraints from relic density determinations, direct detection and collider searches are all satisfied.

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Studies of the rotation curves of galaxies, large scale structures, and recent measurements of the cosmic microwave background radiation, have confirmed that about 23% of the energy in the Universe is in the form of cold dark matter (CDM) [1]. The origin and the nature of CDM is one of the biggest puzzles in both particle physics and cosmology. Since all known particles are ruled out as dark matter candidates, dark matter provides the strongest phenomenological motivation for new physics beyond the Standard Model (SM). The Minimal Supersymmetric Standard Model (MSSM), supplemented with an exact discrete symmetry (R -parity), possesses two natural CDM candidates: the lightest neutralino and the lightest scalar neutrino (sneutrino). The former is a generic mixture of the superpartners of the neutral gauge and Higgs bosons, and its phenomenology has been the subject of extensive studies over the last 20 years [2]. In contrast, the left-handed (LH) sneutrinos of the MSSM have been ruled out as a major component of the dark matter in the Universe, by the combination of cosmological and experimental constraints. More precisely, LH sneutrinos are weakly charged, and typically annihilate too rapidly via Z -mediated s -channel diagrams, resulting in a relic density too small to account for all of the dark matter. To suppress the annihilation rate it was proposed that the sneutrinos should be either very light ($\mathcal{O}(\text{GeV})$) [3] or very heavy ($\mathcal{O}(\text{TeV})$) [4]. However, a very light sneutrino is excluded by the measurement of the invisible width of the Z gauge boson, while a very heavy sneutrino is excluded by direct dark matter searches [4]. Therefore, the LH sneutrinos of the MSSM are now disfavored as dark matter candidates.

On the other hand, the recent evidence of neutrino masses provides strong impetus for extending the particle content of the MSSM with right-handed (RH) neutrinos ν_R and their superpartners, the RH sneutrinos $\tilde{\nu}_R$. This opens up the new possibility that the dark matter is due to a RH sneutrino, whose mass is plausibly in the TeV range. Indeed, if the neutrinos are Dirac, then a light RH neutrino is guaranteed, and its superpartner,

whose mass is solely due to supersymmetry breaking effects, is expected to be around the Terascale. Even if the neutrinos are Majorana particles, the smallness of their masses is naturally explained through a seesaw mechanism, thus requiring the existence of RH Majorana neutrinos at some high scale, which could possibly be as low as the TeV scale. Whether or not the $\tilde{\nu}_R$ is the lightest supersymmetric particle (LSP) in the spectrum depends on the exact mechanism of supersymmetry breaking. In this letter we shall adopt a model-independent approach and simply assume that $\tilde{\nu}_R$ is the LSP whose mass $M_{\tilde{\nu}_R}$ is a free parameter. We shall then investigate the viability of $\tilde{\nu}_R$ as a thermal dark matter candidate.

On the face of it, this idea cannot easily work, since the RH sneutrino is a SM singlet, and cannot be thermalized in the early universe through SM gauge interactions. One approach will be to assume that the $\tilde{\nu}_R$'s are produced non-thermally [5], a scenario which is possible, but not very predictive. Another possibility is to take the LSP as a mixture of LH and RH sneutrinos and adjust the mixing angle to generate an acceptable thermal relic abundance [6]. Here we shall pursue a different direction, namely, extending the MSSM with an additional gauge symmetry, which would allow $\tilde{\nu}_R$ to thermalize and then freeze-out with the proper relic abundance. For simplicity, we shall consider an extra Abelian gauge group $U(1)'$, under which all MSSM fields, as well as the RH sneutrino, are charged. New Abelian gauge symmetries are predicted by many new physics scenarios, including superstrings, extra dimensions, strong dynamics and grand unification. The $U(1)'$ -extended MSSM (UMSSM) [7] can also provide an elegant solution to the fine-tuning problem (μ -problem [8]) of the MSSM when the symmetry is broken at TeV scale. The UMSSM generically predicts a new gauge boson Z' and its superpartner, a Z' -ino \tilde{Z}' , as well as a new singlet Higgs superfield S . All of these new states are expected to have masses near the TeV scale.

Our setup is as follows. We assume three Dirac neutrinos, and correspondingly, three families of RH sneutrinos. The allowed patterns of $U(1)'$ charges are singled out by

requiring that the $U(1)'$ be anomaly-free [9]. Even then, the model will have a large number of free parameters. For simplicity, we shall make use of the $U(1)'$ charges as predicted in E_6 grand unification. The E_6 group contains two additional Abelian gauge groups, $U(1)_\chi$ and $U(1)_\psi$. Assuming only a linear combination of them at the TeV scale, the $U(1)'$ charge Q' of any field is given in terms of its $U(1)_\chi$ charge Q_χ , its $U(1)_\psi$ charge Q_ψ , and the mixing angle θ_{E6} as [7]

$$Q' = Q_\chi \cos \theta_{E6} + Q_\psi \sin \theta_{E6} . \quad (1)$$

This choice allows for tree-level neutrino Yukawa couplings and neutrino mass generation through the usual Higgs mechanism. Because of the smallness of the neutrino masses, the L-R sneutrino mass mixing is extremely suppressed, and the LH and the RH sneutrinos will be naturally decoupled. We will assume that the LSP is the (almost) purely RH sneutrino in this letter, postponing the more general case of mixing with the LH sneutrino for a subsequent publication.

In our numerical analysis, we further assume that any exotic chiral fields which might be required for anomaly cancellation, are very heavy and will not affect the relic density calculation. We shall take the value of the $U(1)'$ gauge coupling constant $g_{Z'}$ to be the GUT motivated value of $g_{Z'} = \sqrt{5/3}g_Y \equiv g_1$ where g_Y is the gauge coupling constant of the hypercharge gauge group $U(1)_Y$. We assume that the lightest RH sneutrino is sufficiently lighter than the other two RH sneutrinos, and is the only dark matter candidate. The generalization to the case of two or three degenerate RH sneutrino families, including the effects of coannihilations, is straightforward, using our results given below.

Due to the presence of the $U(1)'$ gauge interactions, in

the early universe the RH sneutrinos are in thermal equilibrium with the rest of the SM particles. As the temperature drops below $M_{\tilde{\nu}_R}$, they become non-relativistic and eventually freeze-out at some temperature T_F , following the usual scenario. There are several relevant annihilation channels: (1) \tilde{Z}' -mediated t -channel processes $\tilde{\nu}_R \tilde{\nu}_R \rightarrow \nu \nu$, $\tilde{\nu}_R^* \tilde{\nu}_R^* \rightarrow \bar{\nu} \bar{\nu}$, and $\tilde{\nu}_R \tilde{\nu}_R^* \rightarrow \nu \bar{\nu}$; (2) Z' -mediated s -channel processes $\tilde{\nu}_R \tilde{\nu}_R^* \rightarrow f \bar{f}$ (in the final state we consider only the SM fermions, including Dirac neutrino pairs); (3) $\tilde{\nu}_R$ -mediated t -channel and 4-point diagram $\tilde{\nu}_R \tilde{\nu}_R^* \rightarrow Z' Z'$, when $M_{Z'} < M_{\tilde{\nu}_R}$. We will not consider in this letter other possible channels such as annihilation into exotic fermions or Higgs bosons (through the Z' resonance).

The present relic density of sneutrinos is found by solving the Boltzmann equation and is given by

$$\Omega_{\tilde{\nu}_R} h^2 \simeq \frac{1.04 \times 10^9 \text{ GeV}^{-1}}{M_{Pl}} \frac{x_F}{\sqrt{g_*(x_F)}} \frac{1}{a + 3b/x_F} \quad (2)$$

with

$$x_F \equiv \frac{M_{\tilde{\nu}_R}}{T_F} = \ln \left(c \sqrt{\frac{45}{8}} \frac{g_{\tilde{\nu}_R}}{2\pi^3} \frac{M_{\tilde{\nu}_R} M_{Pl} (a + 6b/x_F)}{\sqrt{g_*(x_F)} x_F} \right), \quad (3)$$

where $M_{Pl} = 1.22 \times 10^{19} \text{ GeV}$, $g_{\tilde{\nu}_R} = 1$, $c = 5/4$ and $g_*(x_F)$ is the total effective number of relativistic degrees of freedom at freeze-out. In Eqs. (2) and (3), we used the standard approximation $\langle \sigma v_{\text{rel}} \rangle = a + 6b/x_F$ for the thermally averaged annihilation cross-section times relative velocity. Although this approximation is not very precise near thresholds and resonances, it provides a very good estimate of the cosmologically preferred values for the RH sneutrino masses. The leading contributions for each channel (either a -terms or b -terms) are given by:

$$a_{\nu\nu} = a_{\bar{\nu}\bar{\nu}} = g_{Z'}^4 Q'(\nu_R)^4 M_{\tilde{Z}'}^2 / \left(\pi (M_{\tilde{Z}'}^2 + M_{\tilde{\nu}_R}^2)^2 \right), \quad (4)$$

$$b_{\nu\bar{\nu}} = g_{Z'}^4 M_{\tilde{\nu}_R}^2 Q'(\nu_R)^2 \left((M_{\tilde{Z}'}^2 + M_{\tilde{\nu}_R}^2)^2 (Q'(\nu_L)^2 + Q'(\nu_R)^2) + 2(M_{\tilde{Z}'}^2 + M_{\tilde{\nu}_R}^2)(4M_{\tilde{\nu}_R}^2 - M_{\tilde{Z}'}^2) Q'(\nu_L) Q'(\nu_R) \right. \\ \left. + (-4M_{\tilde{\nu}_R}^2 + M_{\tilde{Z}'}^2)^2 Q'(\nu_R)^2 \right) / \left(12\pi (M_{\tilde{Z}'}^2 + M_{\tilde{\nu}_R}^2)^2 |-4M_{\tilde{\nu}_R}^2 + M_{\tilde{Z}'}^2 - iM_{Z'} \Gamma_{Z'}|^2 \right), \quad (5)$$

$$b_{f\bar{f}} = g_{Z'}^4 Q'(\nu_R)^2 (M_{\tilde{\nu}_R}^2 - M_f^2)^{1/2} (4M_{\tilde{\nu}_R}^2 (Q'(f_L)^2 + Q'(f_R)^2) - M_f^2 (Q'(f_L)^2 - 6Q'(f_L)Q'(f_R) + Q'(f_R)^2)) \\ / \left(48\pi M_{\tilde{\nu}_R} |-4M_{\tilde{\nu}_R}^2 + M_{\tilde{Z}'}^2 - iM_{Z'} \Gamma_{Z'}|^2 \right), \quad (6)$$

$$a_{Z'Z'} = g_{Z'}^4 Q'(\nu_R)^4 (M_{\tilde{\nu}_R}^2 - M_{Z'}^2)^{1/2} (8M_{\tilde{\nu}_R}^4 - 8M_{\tilde{\nu}_R}^2 M_{Z'}^2 + 3M_{Z'}^4) / (16\pi M_{\tilde{\nu}_R}^3 (-2M_{\tilde{\nu}_R}^2 + M_{Z'}^2)^2), \quad (7)$$

where $M_{Z'}$ ($\Gamma_{Z'}$) is the mass (width) of the Z' gauge boson.

Figure 1 shows the relic density $\Omega_{\tilde{\nu}_R} h^2$ of the RH sneutrino versus its mass $M_{\tilde{\nu}_R}$, for $\theta_{E6} = \pi/3$, $g_{Z'} = g_1$, and for fixed $M_{\tilde{Z}'} = 1.5M_{\tilde{\nu}_R}$. Results are shown for

three different values of $M_{Z'}$: 500 GeV (red), 1000 GeV (blue), and 2000 GeV (magenta). The shaded region is the 2σ range of $\Omega_{\text{CDM}} h^2$ allowed by WMAP+SDSS $\Omega_{\text{CDM}} h^2 = 0.111^{+0.011}_{-0.015}$ [1]. The dotted line traces the minimum value of $\Omega_{\tilde{\nu}_R} h^2$ on the Z' resonance. We see

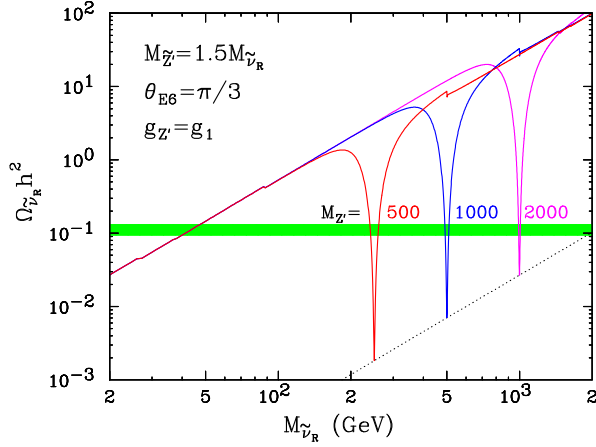


FIG. 1: Relic density $\Omega_{\tilde{\nu}_R} h^2$ of the RH sneutrino versus its mass $M_{\tilde{\nu}_R}$, for $\theta_{E6} = \pi/3$, $g_{Z'} = g_1$, and fixed \tilde{Z}' mass as $M_{\tilde{Z}'} = 1.5 M_{\tilde{\nu}_R}$. Results are shown for three different values of $M_{Z'}$: 500 GeV (red), 1000 GeV (blue), and 2000 GeV (magenta). The shaded region is the 2σ range of $\Omega_{\text{CDM}} h^2$ allowed by WMAP+SDSS [1]. The dotted line traces the minimum value of $\Omega_{\tilde{\nu}_R} h^2$ on the Z' resonance.

from Fig. 1 that over much of the parameter space, the RH sneutrino relic density is too large and would overclose the Universe. This is expected, given the absence of any SM interactions for the $\tilde{\nu}_R$. However, Fig. 1 also reveals the existence of at least two generic regions which yield acceptable values for $\Omega_{\tilde{\nu}_R} h^2$. First, for the chosen values of the fixed parameters, there is a region around $M_{\tilde{\nu}_R} = 45$ GeV, where t -channel annihilation through the relatively light \tilde{Z}' is sufficient to reduce $\Omega_{\tilde{\nu}_R} h^2$ to the desired values and below. In general, the location of this region (which is in a sense analogous to the “bulk” dark matter region of minimal supergravity) is given by

$$\frac{M_{\tilde{\nu}_R}}{9 \text{ TeV}} \sim g_{Z'}^2 Q'(\nu_R)^2 \frac{r}{1+r^2}, \quad r \equiv \frac{M_{\tilde{Z}'}}{M_{\tilde{\nu}_R}}. \quad (8)$$

In addition, there is a Z' resonance “funnel” region at

$$M_{\tilde{\nu}_R} \sim \frac{1}{2} M_{Z'}. \quad (9)$$

For the chosen values of the fixed parameters, this region is present over the whole range of sneutrino masses shown. As the Z' mass increases, however, the resonant dip in $\Omega_{\tilde{\nu}_R} h^2$ becomes more and more shallow, and eventually disappears for $M_{Z'} \gtrsim 4$ TeV (with this choice of the fixed parameters). Finally, a new channel $\tilde{\nu}_R \tilde{\nu}_R^* \rightarrow Z' Z'$ opens up for $M_{\tilde{\nu}_R} > M_{Z'}$, as evidenced by the kinks at $M_{\tilde{\nu}_R} \sim M_{Z'}$. With our choice of E_6 charge assignments, the $Z' Z'$ channel is unable by itself to satisfy the relic density constraint, but may become relevant and provide a third good dark matter region if $g_{Z'}$ and/or the $U(1)'$ charges Q' are assumed to be larger.

The nucleus-dark matter interaction is given by the

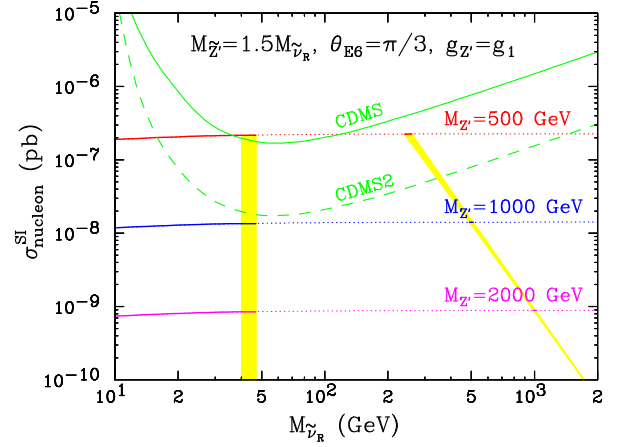


FIG. 2: Spin-independent cross-section (normalized to a single nucleon) of the sneutrino-nucleus interaction versus $M_{\tilde{\nu}_R}$ for a Germanium type detector, for the same parameter choices as in Fig. 1. The dotted (solid) portions of the curves correspond to unacceptable (acceptable) values for $\Omega_{\tilde{\nu}_R} h^2$, while in the yellow shaded region $\tilde{\nu}_R$ can singlehandedly explain all of the dark matter in the Universe. The green curves are the current (solid) and projected (dashed) limits from the CDMS experiment [10].

effective Lagrangian,

$$\mathcal{L}_{eff}(\chi, q) = i \frac{g_{Z'}^2}{M_{Z'}^2} Q'(\nu_R) (\tilde{\nu}_R^* \partial_\mu \tilde{\nu}_R - \partial_\mu \tilde{\nu}_R^* \tilde{\nu}_R) \times \left[\sum_{i=u,d} Q'_V(q_i) \bar{q}_i \gamma_\mu q_i + \sum_{i=u,d} Q'_A(q_i) \bar{q}_i \gamma_\mu \gamma_5 q_i \right] \quad (10)$$

where $Q'_V(q_i)$ and $Q'_A(q_i)$ are the vector and axial charges of the quark q_i , respectively. In the non-relativistic limit the time component of the vector current dominates which gives the spin-independent elastic scattering cross-section

$$\sigma_{\text{nucleon}}^{\text{SI}} = \frac{\lambda_N^2}{\pi A^2} \mu_n^2, \quad (11)$$

where μ_n is the effective mass of the nucleon and the sneutrino, and $\lambda_N = Z\lambda_p + (A-Z)\lambda_n$, with

$$\lambda_p = \frac{g_{Z'}^2}{M_{Z'}^2} Q'(\nu_R) [2Q'_V(u) + Q'_V(d)],$$

$$\lambda_n = \frac{g_{Z'}^2}{M_{Z'}^2} Q'(\nu_R) [2Q'_V(d) + Q'_V(u)]. \quad (12)$$

Figure 2 shows our result for the spin-independent elastic scattering cross-section of the sneutrino dark matter in a Ge-type detector such as CDMS, for the same parameter choices as in Fig. 1. The solid (dashed) green curves are the current (projected for CDMS2) limits from the CDMS experiment [10]. The predicted cross-sections are almost flat over the whole range $M_{\tilde{\nu}_R} \gtrsim 10$ GeV because $\mu_n \sim M_n = \text{const}$ for $M_{\tilde{\nu}_R} \gg M_n$. The three curves

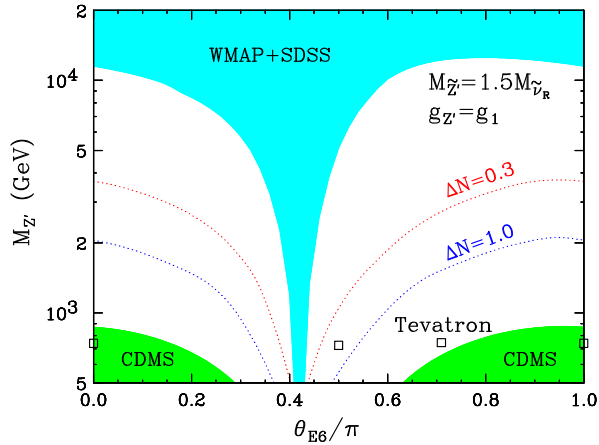


FIG. 3: Experimental constraints on the $(\theta_{E6}, M_{Z'})$ parameter space in the resonance funnel region $M_{\tilde{\nu}_R} \sim M_{Z'}/2$, for fixed $g_{Z'} = g_1$ and $M_{\tilde{Z}'} = 1.5M_{\tilde{\nu}_R}$. The upper (light blue) shaded region is cosmologically excluded, while the lower (green) shaded region is currently ruled out by CDMS. The squares indicate the most recent Z' mass bounds from CDF [11]. The dotted curves [12] are the lower bounds on $M_{Z'}$ from the discrepancy in the ${}^4\text{He}$ abundance, for an effective neutrino mass of $\Delta N = 0.3$ (upper, red curve) and $\Delta N = 1$ (lower, blue curve), and for $T_c = 150$ MeV. The singular point $\theta_{E6} = 0.42\pi$ corresponds to $Q'(\nu_R) = 0$.

are related by simple scaling, since $\sigma_{\text{nucleon}}^{\text{SI}} \sim M_{Z'}^{-4}$. It is clear that by increasing the Z' mass one can effectively suppress the elastic scattering cross-section and avoid the direct detection constraint. However, even for the lowest Z' masses allowed by the Tevatron, currently there is no direct detection constraint on $\tilde{\nu}_R$ dark matter for the parameter choices in Figs. 1 and 2.

We have already seen that in the “bulk” $\tilde{\nu}_R$ region (8) the relic density and the direct detection rates depend on different parameters ($M_{\tilde{Z}'}$ and $M_{Z'}$, respectively), which to a large extent guarantees its viability. Therefore, we shall now concentrate on the resonance “funnel” region (9), allowing also for variations in θ_{E6} , and accumulate all relevant experimental constraints in the $(\theta_{E6}, M_{Z'})$ parameter plane. The results are shown in Fig. 3, for fixed $g_{Z'} = g_1$ and $M_{\tilde{Z}'} = 1.5M_{\tilde{\nu}_R}$. The upper (light blue) shaded region is cosmologically excluded: we have already seen in Fig. 1, that for any given value of $g_{Z'}$, θ_{E6} and $M_{\tilde{Z}'}$, there is an upper limit on $M_{Z'}$, beyond which the relic density is too large, even on resonance. The lower (green) shaded region is currently ruled out by the direct detection search at CDMS. The dotted curves are the lower bounds on $M_{Z'}$ from requiring that the ${}^4\text{He}$ abundance discrepancy be explained by light Dirac neutrinos coupled to Z' , for two values of the effective neutrino number: $\Delta N = 0.3$ (upper, red curve) and $\Delta N = 1$ (lower, blue curve), and for a choice of QCD phase transition temperature $T_c = 150$ MeV [12, 13]. For a larger value of T_c , the curves will be shifted to higher values

of $M_{Z'}$. The Tevatron dilepton search provides typical bounds on the Z' mass in the range $600 \sim 900$ GeV, depending on the $U(1)'$ charges [11]. The squares indicate the most recent Z' mass bounds from CDF within the E_6 model. The singular point $\theta_{E6} \sim 0.42\pi$ corresponds to $Q'(\nu_R) \sim 0$, when the RH sneutrino is (almost) decoupled and the Universe is overclosed.

The collider implications of the $\tilde{\nu}_R$ LSP scenario are quite interesting, especially at hadron colliders such as the LHC. A sneutrino LSP would manifest itself as missing energy in the detector, just like any other dark matter candidate. Since spin determinations at the LHC are rather challenging, it is interesting to see whether this scenario can be discriminated from the usual case of neutralino LSP in supersymmetry, or its look-alike scenario of Universal Extra Dimensions [14].

The prospects for indirect detection of $\tilde{\nu}_R$ dark matter do not appear very promising, since the a terms in most of the annihilation channels are vanishing. One exception are the RH neutrino final states, which unfortunately lead to neutrino detection rates suppressed by the small Dirac neutrino mass. The other nonvanishing a -term is in the $Z'Z'$ final state, which only opens up for $M_{\tilde{\nu}_R} > M_{Z'}$, and for the typical values of the parameters considered here is rather small.

In this letter, we showed that in a natural extension of the MSSM with a new Abelian gauge symmetry $U(1)'$, the RH sneutrino $\tilde{\nu}_R$ is a viable thermal dark matter candidate, satisfying all relevant experimental constraints. Our scenario is very generic and does not rely on the particular choice of the E_6 charge assignments (1), or the specific mechanism for solving the μ -problem. Our basic assumptions were just two: that there is a light RH neutrino whose superpartner gets its mass from supersymmetry breaking, and that there are new gauge interactions at the TeV scale. We then found two generic parameter space regions ((8) and (9)) with good $\tilde{\nu}_R$ dark matter. Considering the effects of the additional Higgs singlets (either as particles in the final state or intermediate resonances), or the more general case of non-Abelian extra gauge symmetries, will open up new and interesting possibilities for extending this scenario.

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